Ray optics and optical instruments(revision notes)

[TOPIC 1] Reflection, Refraction, Lens and Prism

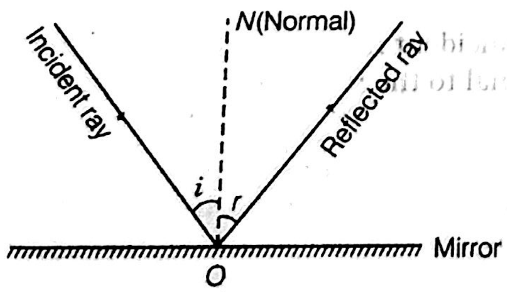
Ray Optics or Geometrical Optics

In this branch of optics, the light is considered as a ray which travels in a straight line.

It states that for each and every object, there is an image. It deals with the phenomena of reflection and refraction of light by ordinary geometrical methods.

1.1 Reflection of Light

Reflection is the phenomenon of changing the path of light after incidenting on a smooth surface without any change in the medium.



Reflection from plane surface

The returning back of light in the same medium from which it has come after striking a smooth surface is called reflection of light.

Laws of Reflection

Two laws of reflection are given below:

(i) The angle of incidence i is equal to the angle of reflection r.

i.e. $\angle i = \angle r$

(ii) The incident ray, reflected ray and normal to the reflecting surface at the point of incidence all lie in the same plane.

Types of Mirror

There are two types of mirror

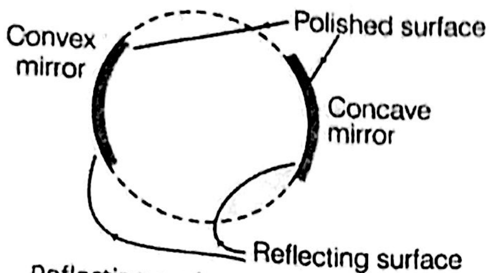
(i) **Plane Mirror** In a plane mirror, image formed is always virtual, erect equal in size as that of the object and at the same distance behind the mirror as the object is in front of the mirror. Image in a plane mirror is always laterally inverted.

(ii) **Spherical Mirror** A type of mirror whose reflecting surfaces is part of a hollow sphere.

Spherical mirrors are also of two types

(a) Concave spherical mirror

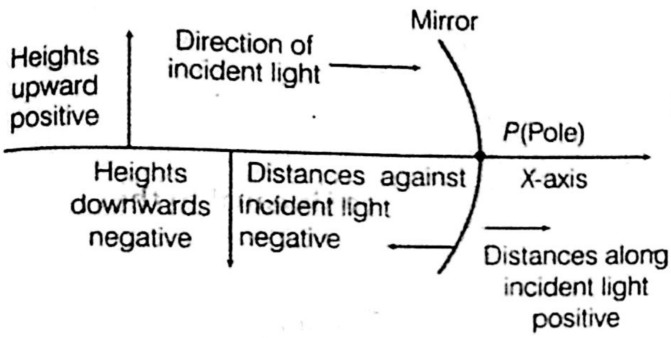
(b) Convex spherical mirror



Reflecting surface of spherical mirror

Sign Convention All measurements should be taken from pole of mirror.

- All measurements along the direction of incident ray will be positive and opposite to incident ray are negative.
- All the measurements for the distances above the principal axis are taken as positive and below the principal axis are taken as negative.
- For a real object, u is negative whereas v is negative for real image and positive for virtual image.



Sign convention

Mirror Formula

Mirror formula is a relation between focal length of the mirror, distances of object and image from the mirror.

$$1/v + 1/u = 1/f$$

where, f = focal length, u = distance of the object from mirror, v = distance of the image from mirror.

Focal length of mirror

(f) = Radius of curvature $(R)/2 \Rightarrow f = R/2$

Linear Magnification

The ratio of the size of the image formed by a spherical mirror I to the size of the object O is called the **linear magnification** produced by the spherical mirror.

$$m = I/O = -v/u = f/f-u = f-v/f$$

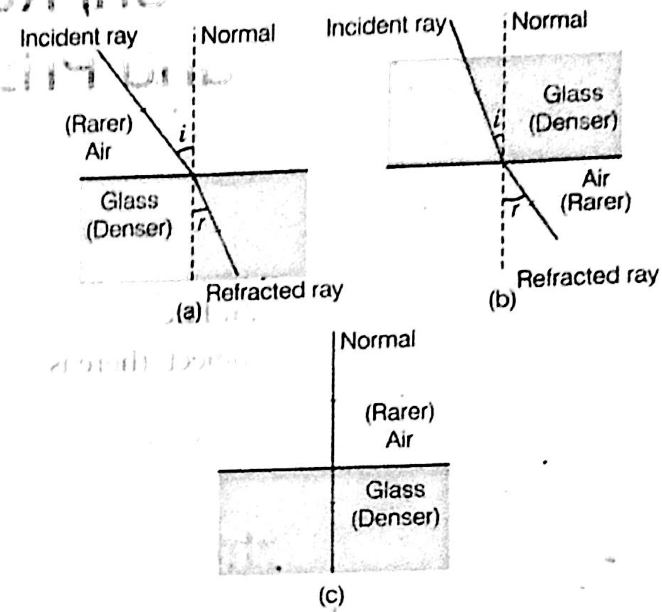
where, I = height of image and O = height of object

Magnification (m)

It is negative for real image and positive for virtual image.

1.2 Refraction

The phenomenon of changing the path of light as it goes from one transparent medium to another is called refraction.



Laws of Refraction

Two laws of refraction are given as below:

(i) The incident ray, refracted ray and the normal to the refracting surface at the point of incidence lie in the same plane.

(ii) The ratio of the sine of the angle of incidence to the sine of the angle of refraction is constant for the two given media. This constant is denoted by μ and is called the **relative refractive index**.

$$\boxed{{}_1\mu_2 = \frac{\sin i}{\sin r} \quad \text{(Snell's law)}}$$

where, ${}_1\mu_2$ is refractive index of the second medium with respect to first medium.

Absolute Refractive Index

The refractive index (μ) of a medium is the ratio of the speed of light (c) in vacuum to the speed of light in the medium (v).

Mathematically, refractive index is given by the relation

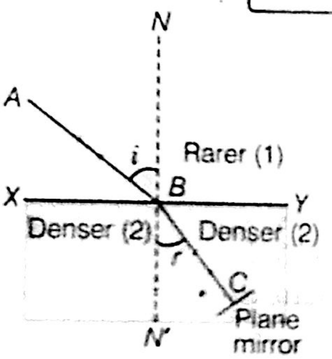
$$\boxed{\mu = \frac{\text{Speed of light in the vacuum}}{\text{Speed of light in the medium}} = \frac{c}{v}}$$

It is also referred to as absolute refractive index of the medium.

Principle of Reversibility of Light

Principle of reversibility of light states that when final path of a ray of light after suffering any number of reflections and refractions is reversed, the ray retraces its path, exactly.

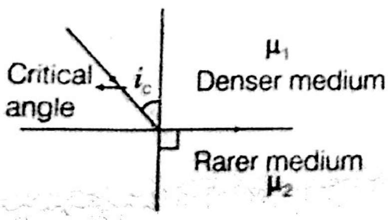
$$\Rightarrow \quad {}_1\mu_2 \times {}_2\mu_1 = 1 \Rightarrow \boxed{{}_2\mu_1 = \frac{1}{{}_1\mu_2}}$$



Principle of reversibility of light

Critical Angle (i_c)

The angle of incidence in denser medium for which angle of refraction in rarer medium is 90° is called the critical angle of the denser medium.



$$\mu_1 \sin i = \mu_2 \sin r \quad \left[\begin{array}{l}\text{when } i = i_c, r = 90^\circ \\ \frac{\sin i_c}{\sin 90^\circ} = {}_2\mu_1 = \frac{1}{{}_1\mu_2}\end{array}\right]$$

or $\quad \mu_1 \sin i_c = \mu_2 \sin 90^\circ$

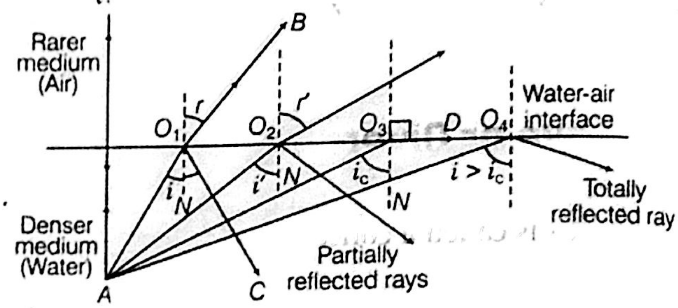
$\Rightarrow \quad \sin i_c = \mu_2/\mu_1 = {}_2\mu_1 = 1/\mu$

$$\boxed{\mu = \frac{1}{\sin i_c}}$$

where, μ = refractive index of denser medium w.r.t. rarer medium.

Total Internal Reflection (TIR)

When a ray of light travelling from denser medium to rarer medium is incident at the interface of two medium at an angle greater than the critical angle for the two media, the ray is totally reflected back to denser medium. This phenomenon is called Total Internal Reflection. It occurs only when angle of incidence in denser medium is greater (not equal) than critical angle, i.e. $i > i_c$.

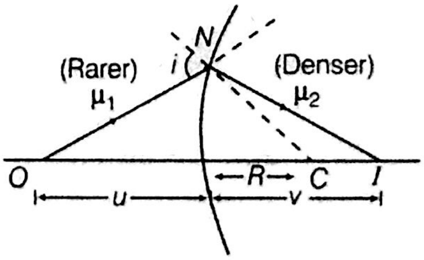


Total Internal Reflection

Refraction at a Spherical Surface

There are two refraction at a spherical surface

(i) Refraction formula for refraction by convex or concave spherical refracting surface is given by



$$\boxed{\frac{\mu_2}{v} - \frac{\mu_1}{u} = \frac{\mu_2 - \mu_1}{R}}$$

where μ_1, μ_2 are refractive index of rarer and denser media and u, v and R are to be taken with their proper signs.

(ii) When refraction takes place from denser to rarer medium, then

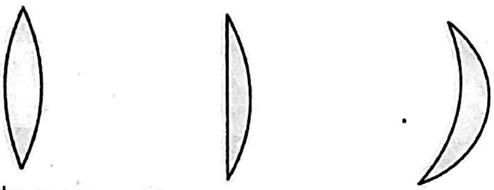
$$\frac{\mu_1}{v} - \frac{\mu_2}{u} = \frac{\mu_1 - \mu_2}{R}$$

1.3 Lens

Lens is a transparent medium bounded by two surfaces of which one or both surfaces are spherical.

Convex or Converging Lens

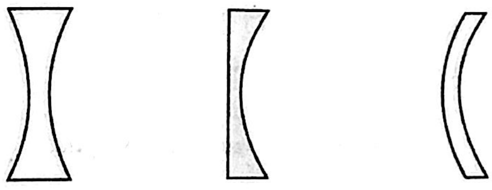
A lens which is thicker at the centre and thinner at its end is called convex lens. *Convex lenses are of three types which are given as below:*



Double convex lens   Plano-convex lens   Concavo-convex lens

Concave or Diverging Lens

A lens which is thinner at the centre and thicker at its ends is called a concave lens. *Concave lenses are of three types which are given as below:*



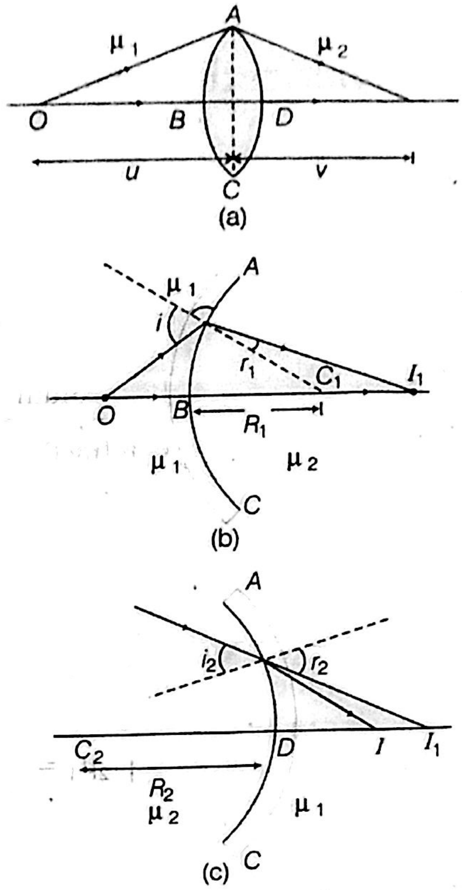
Double concave lens   Plano-concave lens   Convexo-concave lens

Lens Maker's Formula for a Convex Lens

This formula relates the focal length of a lens to the refractive index of lens and radii of curvature of two surfaces.

$$1/f = (\mu - 1)(1/R_1 - 1/R_2)$$

μ = refractive index of material of lens w.r.t. surrounding media and R_1, R_2 = radii of curvatures of two surfaces.



There are some important points related to Lens maker's formula

When lens of refractive index μ is immersed in a medium of refractive index μ', then

(i) When lens is taken in another medium, then focal length changes to f_m which is given by

$$\frac{1}{f_m} = \left(\frac{\mu}{\mu'} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \quad \ldots\text{(i)}$$

(ii) If $\mu' = 1$, i.e. medium is air, the focal length of lens (i.e. f_a) is given by

$$1/f_a = (\mu - 1)(1/R_1 - 1/R_2) \quad \ldots\text{(ii)}$$

(iii) $\dfrac{f_m}{f_a} = \dfrac{(\mu - 1)}{\left(\dfrac{\mu}{\mu'} - 1\right)}$ [dividing Eq. (ii) by Eq. (i)]

(iv) If $\mu = \mu' \Rightarrow f_m = \infty$

⇒ lens behaves like a glass slab.

(v) If $\mu < \mu'$ ⇒ $f_m > f_a$ and nature reversed.

(vi) If $\mu > \mu'$ ⇒ $f_m > f_a$ and nature remains same.

Linear Magnification Produced by a Lens

Linear magnification of a lens is defined as, the ratio of the height of the image formed by the lens and height of the object.

Linear magnification, $m = \dfrac{\text{Height of image}(I)}{\text{Height of object}(O)}$

For Convex Lens

CASE I When image is real, $m = -I/O = v/-u$

When image is real, it is inverted and forms on the other side of object.

CASE II When image is virtual, $m = I/O = v/u$

When image is virtual, it is erect and forms on the same side of object.

Thus, it can be said that convex lens gives positive linear magnification for virtual image and negative linear magnification for real image.

For Concave Lens

Concave lens always forms virtual image, linear magnification of concave lens, $m = I/O = v/u$.

Concave lens always gives positive linear magnification. *Other formula for linear magnification are*

$$m = v/u = f - v/f = f/f + u$$

(i) If $|m| > 1$ ⇒ image is magnified.

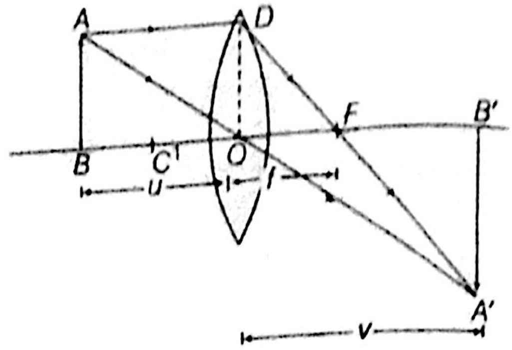
(ii) If $|m| < 1$ ⇒ image is diminished.

(iii) If $|m| = 1$ ⇒ image is of same size as the object.

Thin Lens Formula

It is a relation between focal length of a lens and distances of objects and image from optical centre of the lens.

Lens formula $1/f = 1/v - 1/u$



Power of Lens

The ability of a lens to converge or diverge the rays of light incident on it. It is called the power of the lens.

Thus, $P = 1/f$ (in m)

SI unit of power of lens is dioptre (D) or m^{-1}

Power of combination of lenses in contact is given by

$$P = P_1 + P_2 + \ldots + P_n \Rightarrow \frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} + \ldots + \frac{1}{f_n}$$

NOTE Magnification by combination of lenses

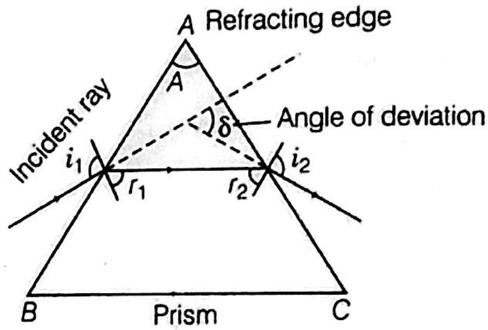
$m = m_1 \times m_2 \times m_3$ ......

1.4 Prism

Prism has the property of bending the incident light towards its base.

A prism is a wedged shaped portion of a transparent medium bounded by two plane faces inclined to each other at a suitable angle.

We get, $r_1 + r_2 = A$ and $\delta = i_1 + i_2 - A$



When the prism is adjusted at angle of minimum deviation, then

(a) angle of incidence is equal to the angle of emergence

(b) $i_1 = i_2$, $r_1 = r_2$, $\delta = \delta_m$, $A + \delta_m = 2i$ and $2r = A$.

(c) $\mu = \sin\left(\frac{A+\delta_m}{2}\right)/\sin\frac{A}{2}$

$\Rightarrow \delta_m \approx (\mu - 1)A$ (for small angle of prism)

Scattering of Light

It is a phenomena in which light is deflected from its path due to its interaction with the particles of the medium through which it passes.

Rayleigh Law of Scattering

It states that the intensity of light of wavelength λ present in the scattered light is inversely proportional to the fourth power of λ, provided the size of scattering particles are much smaller than λ, Mathematically scattering $\propto \frac{1}{\lambda^4}$ [for $a << \lambda$]. The bluishness of sky and reddishness of sky during sunrise and sunset could be explained by this law.

[TOPIC 2] Optical Instruments

Near Point and Far Point of Human Eye

- **Near Point** (D) The minimum distance from the eye at which an object can be seen most distinctly without any strain. For a healthy normal eye, it is 25 cm. It is also known as least distance of distinct vision.
- **Far Point** The farthest point from the eye, at which an object can be seen clearly by the eye is called the far point of the eye. For a normal eye, the far point is at infinity.

Simple Microscope
(Magnifying Glass)

It is a converging lens of short focal length, held close to the eye.

***Case* I** When image is formed at the near point. Then,

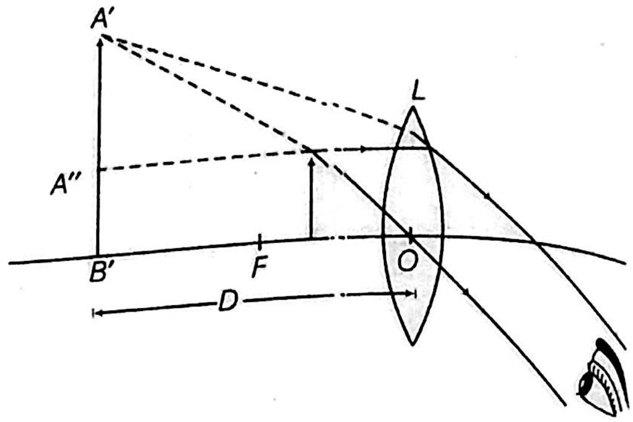
$$M = 1 + \frac{D}{f}$$

In the case of when eye is placed behind the lens at a distance a, then

$$M = 1 + \frac{(D-a)}{f}$$

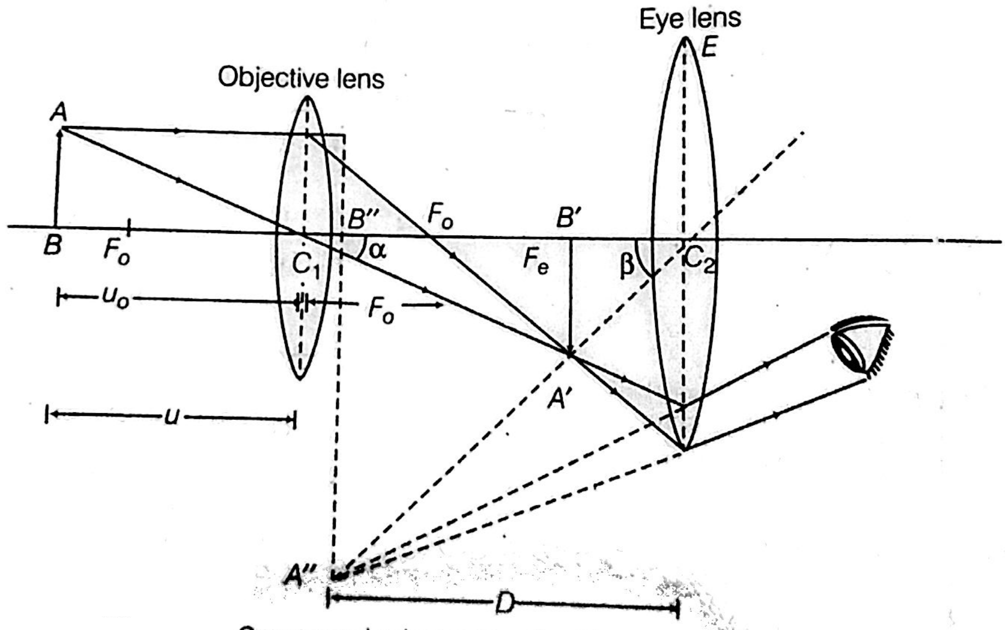
***Case* II** When the image is formed at, the infinity.

$$M = \frac{D}{f}$$



Compound Microscope

It is an optical device which consists of two convex lenses, one objective of very small focal length with short aperture and one eyepiece, E of moderate focal length and large aperture.



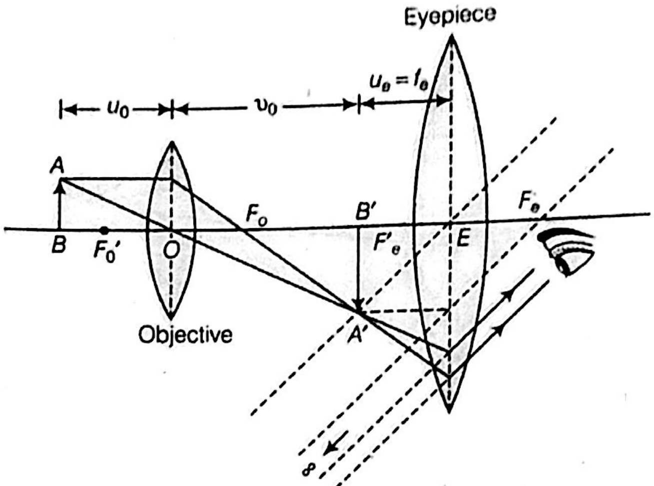
Compound microscope, final image at D.

Magnifying power, $\boxed{M = m_e \times m_o}$

where, m_e and m_o are the individual magnifying powers of objective and eye lens.

$M = \frac{v_o}{u_o}\left(1 + \frac{D}{f_e}\right)$, when final image is at near point.

$M = \frac{v_o}{u_o} \times \frac{D}{f_e}$, when final image is at the infinity $= \frac{L}{f_0} \times \frac{D}{f_e}$, where L = Distance between the two lenses = tube length.

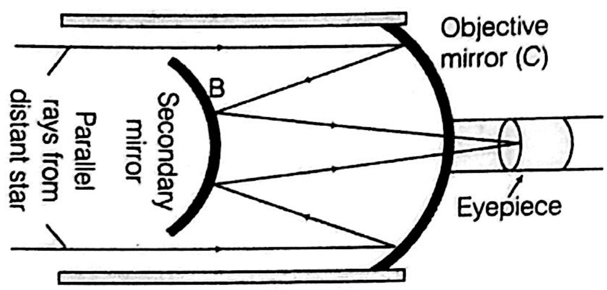


Compound microscope, final image at infinity.

i.e. when the final image is formed at infinity, the length of the compound microscope, $\boxed{L = v_o + f_e}$

Reflecting Astronomical Telescope

These telescopes form image free from chromatic aberration and spherical aberration.



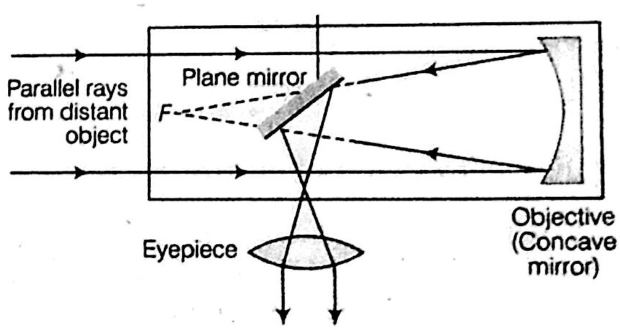
Schematic diagram of cassegrain reflecting telescope

The two types of reflecting telescopes are

(i) Newtonian reflecting telescope.

(ii) Cassegrain reflecting telescope.

Magnification, $\boxed{m = \frac{f_o}{f_e}\left(1 + \frac{f_e}{D}\right)}$



For final image formed at infinity,

where, $\boxed{f_o = \frac{R}{2}}$ and $\boxed{m = \frac{f_o}{f_e} = \frac{R/2}{f_e}}$

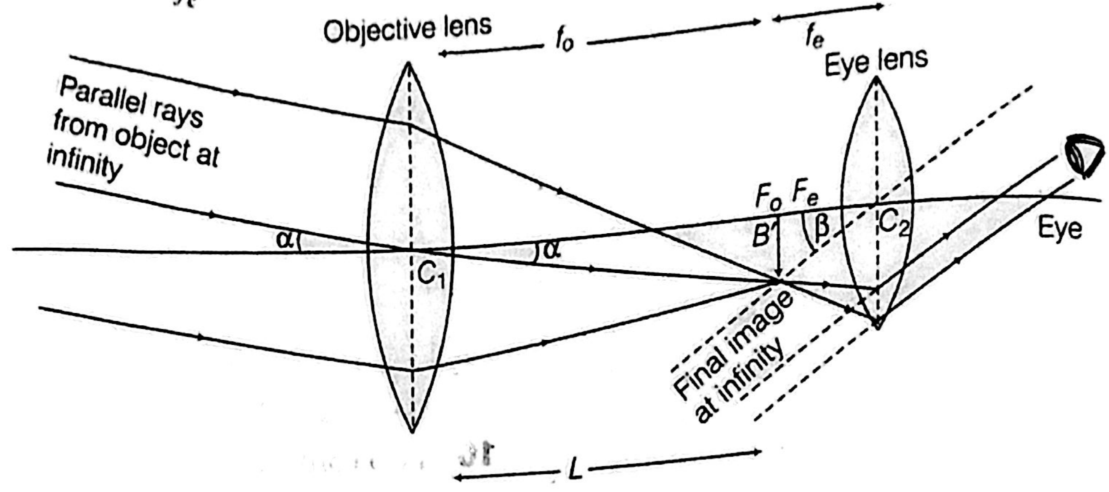
and R is the radius of curvature of objective mirror.

Refracting Astronomical Telescope

It consists of an objective lens of a large focal length (f_o) and large aperture, also an eye lens of small aperture and focal length.

(i) Magnification when final image is formed at infinity,

Magnification, $m = -\frac{f_o}{f_e}$ and length of telescope, $\boxed{L = |f_o| + |f_e|}$

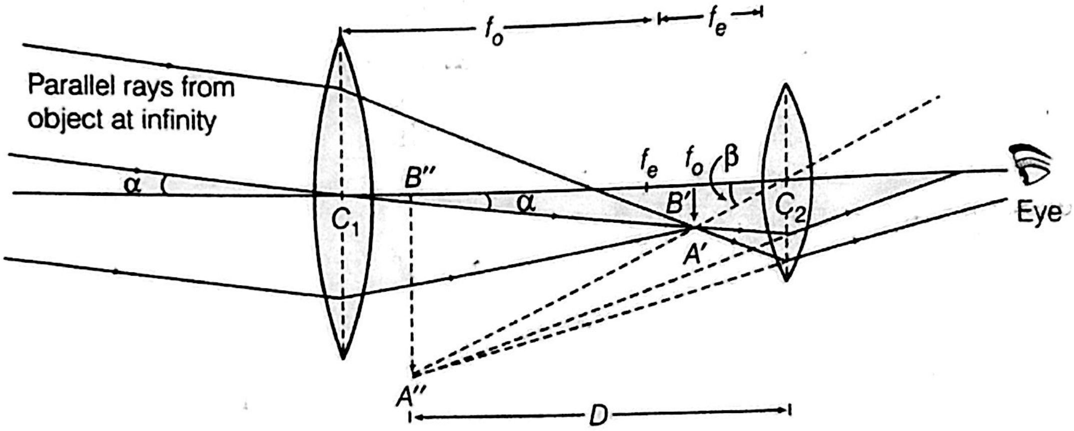


(ii) When the final image is formed at D,

Magnification, $m = -\frac{f_o}{f_e}\left(1 + \frac{f_e}{D}\right)$

Length of telescope,

$$\boxed{L = |f_o| + \frac{f_e D}{f_e + D}}$$



Resolving Power

- Resolving power of microscope $= \frac{1}{d} = \frac{2\mu \sin\theta}{\lambda}$, Resolving power $\propto \frac{1}{\lambda}$

where, $\mu \sin\theta$ = numerical aperture, θ is the semi-vertical angle of the cone formed by object at objective, $\mu = RI$ of the medium between object and lens and d = minimum distance between two objects whose image can be seen through microscope vivid and clear. λ is a wavelength of light used to illuminate the object.

• Resolving power of a telescope $= \frac{1}{\Delta\theta} = \frac{D}{1.22\lambda}$

$\Rightarrow$ Resolving power $\propto \frac{1}{\lambda}$

where, D is the diameter or aperture of objective lens and λ is the wavelength of light used.